

Resolving Magnetic and Chemical Heterogeneity Using Resonant Soft X-Ray Small-Angle Scattering

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INTRODUCTION

Magnetic disorder is ubiquitous in bulk and thin film magnetic materials, resulting from, e.g., domain structure during magnetization reversal, fluctuations near phase transitions, and chemical heterogeneity common in alloys and compounds. Characterizing magnetic heterogeneity and resolving it from chemical heterogeneity have remained difficult experimental challenges, especially when they coexist on nanometer size scales impossible to probe by many techniques. We are developing resonant small-angle scattering techniques that can clearly resolve magnetic and chemical heterogeneity down to nanometer size scales.¹

Co/Pt multilayers having perpendicular magnetic anisotropy are ideal systems to develop these techniques, in part because they have distinct sources of magnetic and charge scattering. Samples were designed to have low remnant magnetization (see Fig. 2 below) to yield a high density of randomly oriented magnetic domains at zero applied field. Measurements were made using the reflectometer on beamline 6.3.2 and Kortright's endstation on undulator beamlines 8.0 and 4.0. Like with Faraday and Kerr magneto-optical effects, linear polarization is appropriate for magnetic scattering because it is resolved by the samples into opposite helicity circular components that each scatter independently from magnetic heterogeneity.

SCATTERING IN RECIPROCAL SPACE

The symmetric transmission geometry was used to constrain scattering vector \mathbf{q} to the plane of the film to optimize coupling to the in-plane spatial distribution of magnetization. Scattering from a sample grown on a SiN_x membrane at ambient temperature having nominal structure SiN_x(160 nm)/Pt(20 nm)/[Co(0.6 nm)/Pt(0.4 nm)]₅₀/Pt(3 nm) is shown in Fig. 1. This scattering was measured at photon energy corresponding to the peak intensity at the Co L_3 line (below) in a weak applied field (0.1 T) and at saturation (1.1 T). Two peaks are evident at low field, and the low- q peak vanishes at saturation. This field dependence identifies the low- q peak, corresponding to an in-plane distance of 150 nm, as resulting from magnetic scattering. The domain structure at zero field was measured with both the XM1 zone plate imaging microscope (beamline 6.1.2) and magnetic force microscopy. The power spectral density (PSD) of the domain contrast

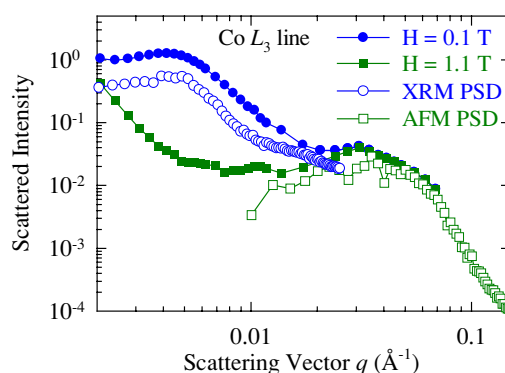


Figure 1. Measured resonant small-angle scattering from Co/Pt multilayer near remanence (0.1 T) and at saturation (1.1 T) are given by solid symbols. Open symbols are PSD of magnetic domain image and the surface height as measured by AFM.

obtained from the x-ray image is scaled and plotted in Fig. 1, confirming that the low- q peak results from the interference of scattering from adjacent domains. The PSD from an atomic force microscope (AFM) image is also scaled and plotted showing excellent agreement with the high- q peak. The AFM image is typical of polycrystalline films, confirming that the high- q peak results from height fluctuations of adjacent columnar grains or related inter-granular heterogeneity having characteristic distance of 20 nm.

SCATTERING VS APPLIED FIELD

The field dependence of the magnetic scattering complements both its q dependence and the field dependence of the average or net magnetization, as shown in Fig. 2. The top panel shows the *average* magnetization as measured by resonant Faraday rotation² below the Co L_3 line. The bottom panel shows *deviations from average* magnetization as measured scattering at the low- q peak. For reversal from negative saturation, the domain nucleation and saturation fields, H_N and H_S , respectively, show clear agreement between the two measurements. The scattering increases by orders of magnitude from H_N to its value at the peak field H_P . H_P represents the field of maximum magnetic disorder and is expected to occur when half of the magnetization has switched irreversibly. Surprisingly, the nonzero H_P for this sample is larger than the coercive field and does not correlate with a feature of the average magnetization loop, highlighting the importance of direct measurements of the magnetic disorder.

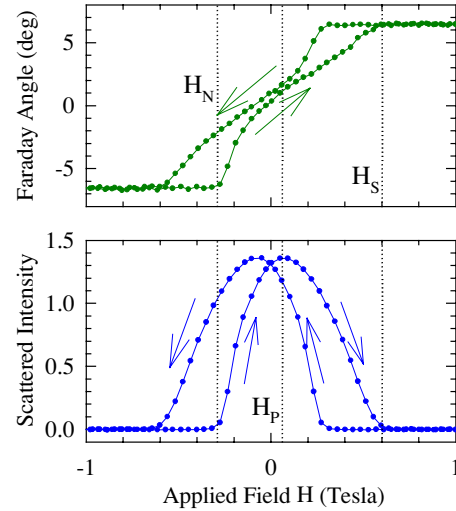


Figure 2. Hysteresis loop of average magnetization measured using Co resonant Faraday rotation (top). Loop measured using Co resonant scattering at the low- q peak (bottom).

SCATTERING VS ENERGY

While the above data leave little uncertainty about the magnetic origin of the low- q peak, not all samples will so readily reveal their magnetic and chemical contributions to scattering. We have found that the energy spectra of the scattering reveal the magnetic and charge contributions, as demonstrated in Fig. 3. The top panel shows a spectrum measured at H_P at the low- q peak. The line through the measured data (points) is a scaled, calculated spectrum using measured magneto-optical scattering factors for Co and a scattering model assuming predominantly pure magnetic scattering (plus a very small charge background). The strong positive peaks at both the L_3 and L_2 lines are characteristic of pure magnetic scattering. The bottom panel shows a spectrum measured at saturation at the high- q peak. The line through these measured data is a model calculation assuming pure charge scattering composed of both Co and Pt contributions, with no magnetic contribution. The bi-polar resonances at the L_3 and L_2 lines are characteristic of pure charge scattering. Measured spectra at other q and H values generally contain a superposition of pure magnetic and charge contributions as determined by model calculations. These results reveal that the scattering spectra themselves contain information

about the relative amount of magnetic and charge contributions to the total scattering that can be modeled to gain this information.

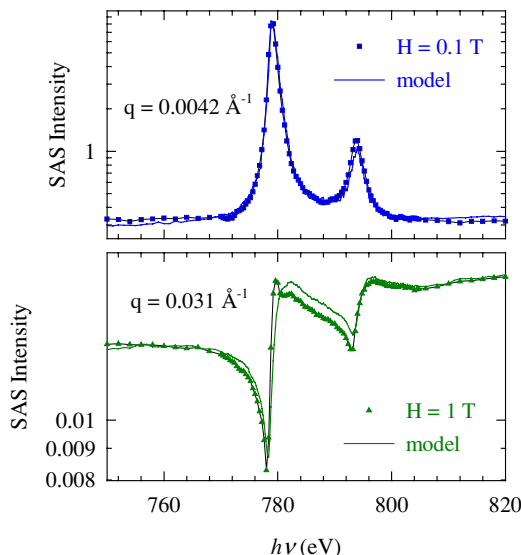


Figure 3. Experimental SAS spectra (points) together with model calculations (lines) using measured Co magnetooptical constants measured at the low- q (top) and high- q (bottom) peaks under field conditions as noted. The calculation at the top assumes predominantly pure magnetic scattering, while the calculation at the bottom assumes entirely chemical (charge) scattering involving both Co and Pt. The strictly positive and bi-polar character of the pure magnetic and pure charge scattering are characteristic of these different scattering sources, and so can be used to infer the source of scattering from measured spectra.

CONCLUSIONS

These results reveal an impressive sensitivity of resonant soft x-ray small-angle scattering to both magnetic and charge heterogeneity at length scales ranging from 300 nm down to 1 nm (in back-scattering geometry at the energies used). For these Co/Pt multilayer samples the resonant energy spectra are sensitive measures of distinctly different magnetic and charge amplitudes, so that modeling can distinguish and quantify these sources and their interference in samples with unknown distributions of charge and magnetic heterogeneity. Continued application of these techniques will provide more information about domain evolution during reversal in the Co/Pt multilayers and related films exhibiting perpendicular magnetic anisotropy. In addition, these resonant scattering techniques offer new opportunities to study nanoscale magnetic and chemical structure and phase transition phenomena in a broad range of samples.

ACKNOWLEDGMENTS

We appreciate help from A.T. Young and E. Arenholz in using beamline 4.0 during its commissioning phase.

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This work was supported by the Director, Office of Energy Research, Office of Basic Energy Sciences, Materials Science Division, of the U.S. Department of Energy under Contract No. DE-AC03-76SF00098.

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